Evolution of three-dimensional cavitation following water entry of an inclined cylinder

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Abstract The water entry of an inclined cylinder is firstly studied experimentally for low Froude number. The cylinder is 50 mm in diameter and 200 mm in length, with a moderate length to diameter ratio. As it is submerged below the water surface, the cavity is fully three-dimensional. Due to the rotation of the cylinder caused by the initial inclined impact, the cavity evolution is quite complicated and a new phenomenon is revealed. The cylinder moves along a curved trajectory in water, which greatly affects the evolution of the cavities. The cavity breaks up into two sub-cavities, and finally collapses because of hydrostatic pressure. [doi:10.1063/2.1202202]

Keywords inclined cylinder, water entry, cavity

The water entry problems of two-dimensional cylinders have been widely studied for a very long time. A typical result of the experimental images was provided by Greenhow and Lin.[1] In their experiment, the flow could be approximated as a two-dimensional one. After that, a lot of studies were conducted to predict the hydrodynamic load both for two-dimensional rigid circular cylinders and elastic cylinders.[2,3] Even nowadays, only a few studies on the water entry of three-dimensional cylinders are reported for the complexity of the problems. As the initial inclined angle is introduced, the phenomenon of the water entry of the cylinders will become more complicated, which is very different from that related to a two-dimensional cylinder.[1] For relatively short cylinders, the length to diameter ratio is small. As the cylinder touches the water surface, the initial impact will cause the cylinder to rotate with relatively larger angular velocity compared with the entry of an inclined "rod" described by Ueda et al.[4] The rotation will obviously influence the evolution of the cavities. For some special inclined angles and length to diameter ratios, the cavity breaks up into two parts. The trajectory of the cylinder in water is curved. These new phenomena will be revealed and discussed as follows.

The schematic illustration of the experimental apparatus is shown in Fig. 1. The Polypropylene cylinder used in the experiment has a density of $\rho = 902$ kg/m^3, diameter of $D = 50$ mm, length of $L = 200$ mm, thus the length to diameter ratio is $L/D = 4$. The contact angle of the cylinder surface is about 98°. The cylinder is cleaned by ethanol only, and no other surface treatment is applied. The initial gravity center of the cylinder is 2.0 m high above the water surface. The impact tank has a dimension of 1.35 m × 1.35 m × 1.35 m, and the water depth is 1.0 m. As the cylinder is released freely by a clamp, it impacts the water with an initial velocity of $V_0 = 6.10$ m/s and an inclined angle

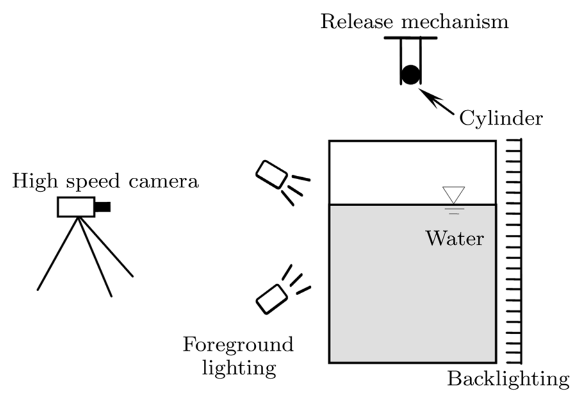

Fig. 1. Schematic illustration of the experimental apparatus.

of 60°. The Froude number is $Fr = V_0/\sqrt{gD} = 8.72$. As the back lighting, foreground lighting and lateral lighting are set in their best conditions (Fig. 1), the high speed digital camera (FASTCAM-APX RS) with a 105 mm Nikon lens is used to study the water entry phenomenon. The camera is arranged at the same height as the water surface. The frame rate is 1 000 per second for the resolution of 1 024 pixel × 1 024 pixel, and the shutter speed is 1/2 500 s.

The cavity evolution following an inclined impact of the cylinder is shown in Fig. 2 by snapshots in time sequence. The curved trajectory and rotation of the cylinder are evident. As the cylinder touches the water surface, a very violent jetting can be observed (Fig. 2(b)) at the initial stage, then the thin water film is driven (Fig. 2(c)). The curved jetting moves with a very high speed and finally breaks up from the whole thin water layer (Fig. 2(d)). The cavitation starts from the fore-end as the cylinder penetrates the water surface. The impact velocity is above the critical velocity to form cavities. The flow separating from the side-face of the cylinder moves almost vertically upwards, while the flow separating from the lower part of the fore-end

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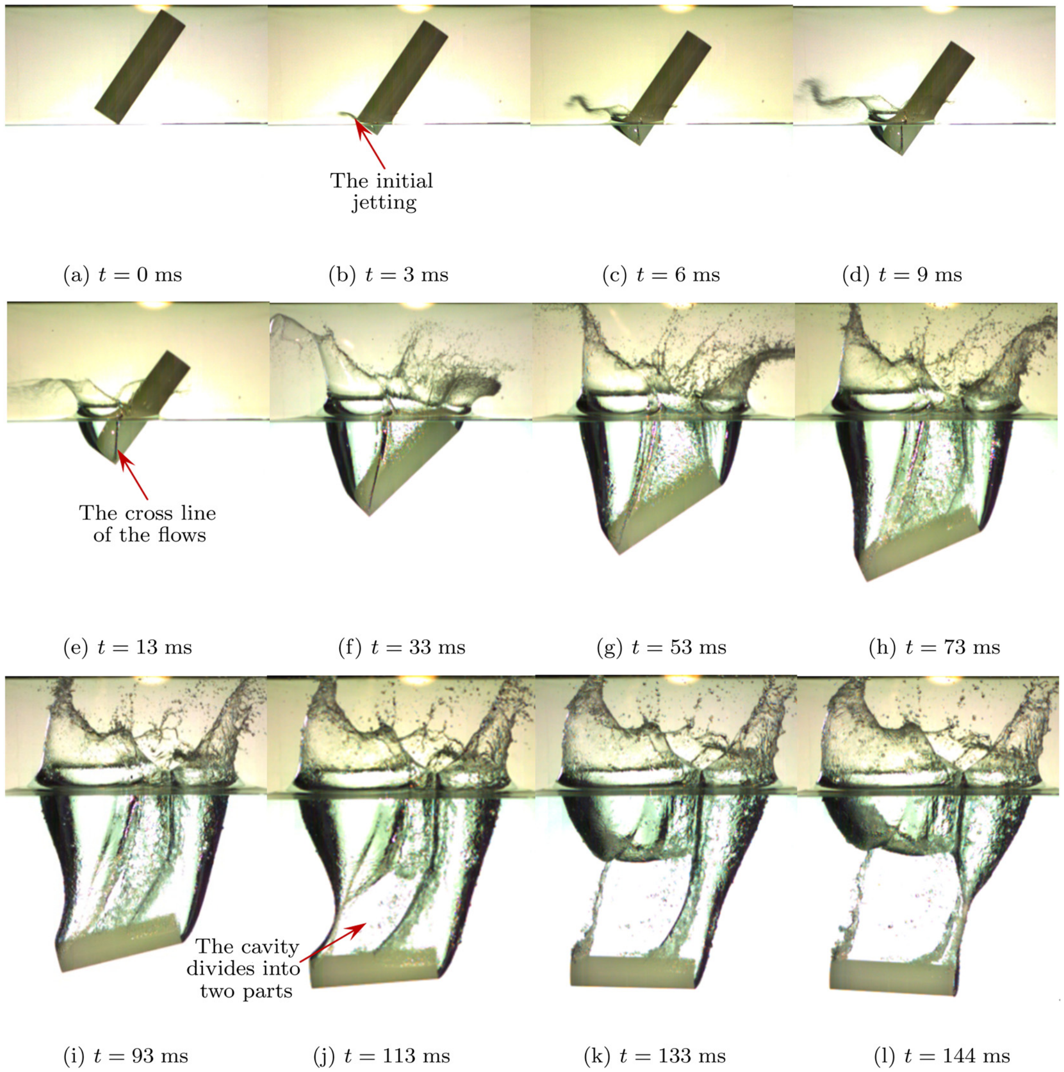

Fig. 2. The image sequence depicting cavity evolution caused by a cylinder with density of 902 kg/m^3. The cylinder is 50 mm in diameter and 200 mm in length. At the time $t = 0$, the cylinder impacts the water surface with an initial impact velocity of $V_0 = 6.10$ m/s and an inclined angle of 60°.

face moves upwards with an obviously lateral motion outwards the paper. The cross lines formed by the two flows can be clearly observed in Figs. 2(e) and 2(f). The cylinder then penetrates the water surface and also creates sub-cavities in the middle and rear-end of the cylinder. Obviously, the width of the cavity in the middle part of the cylinder is smaller than those in the fore-end and rear-end, as revealed in Fig. 2(i). The downwards velocity combined with the lift force due to the rotation caused by the initial impact force greatly affects the development of the cavities. The cavity is later split into two parts, as shown in Fig. 2(j). The left part of the bended cavity is similar to that formed by a spinning sphere[5] and collapses into one point, while the right part of the cavity shifts along the cylinder surface and finally collapses at the rear-end into a line of air bulbs.

As revealed above, when the cylinder impacts the water surface with a relatively high speed, the cavity formed could be regarded as composed of three parts, the cavity formed in the fore-end face, the cavity in the middle and that in the end-face. Thus the length to diameter ratio and the initial inclined angle greatly influence the overall cavity evolution. As the inclined angle decreases, the cavity evolution is similar to that caused by a horizontal cylinder.[6] As the inclined angle increases, it is similar to that caused by a vertical cylinder, the effect of these parameters on the cavity evolution will be discussed in the future.

The effects of the initial inclined angle on the evolution of the cavity as the cylinder impacts on and penetrates into water are not surprising. However, the high-speed camera reveals the formation and evolution of the elegant splash and cavity when the initial inclined angle is introduced. The cavity evolution is fully three-dimensional, and the initial inclined impact will cause the cylinder to rotate. The lift force as a result of the rotation, as well as the downwards velocity pushes the cylinder moving forwards, which greatly influences the collapse of the cavity. The cavity is split into two parts. The left part of the cavity is similar to that formed by a spinning sphere and contracts into a point, both the two cavities finally collapse into bubble lines.

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1. M. Greenhow, and W. M. Lin, *Nonlinear Free Surface Effects: Experiments and Theory* (Department of Ocean Engineering, MIT. 1983).
2. H. Sun, and O. Faltinsen, Ocean Res. **28**, 299 (2006).
3. T. I. Khabakhpasheva, J. Fluid Struct. **25**, 431 (2009).
4. Y. Ueda, T. Uemura, and M. Iguchi, J. Vis. **14**, 7 (2010).
5. T. T. Truscott, and A. H. Techet, J. Fluid Mech. **625**, 135 (2009).
6. Y. Ueda, and Iguchi, J. Vis. **s12**, 650 (2011).